EFFECTS OF SEA-LEVEL RISE AND FRESHWATER MANAGEMENT ON LONG-TERM WATER LEVELS AND WATER QUALITY IN THE FLORIDA COASTAL EVERGLADES

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Research article

Effects of sea-level rise and freshwater management on long-term water levels and water quality in the Florida Coastal Everglades

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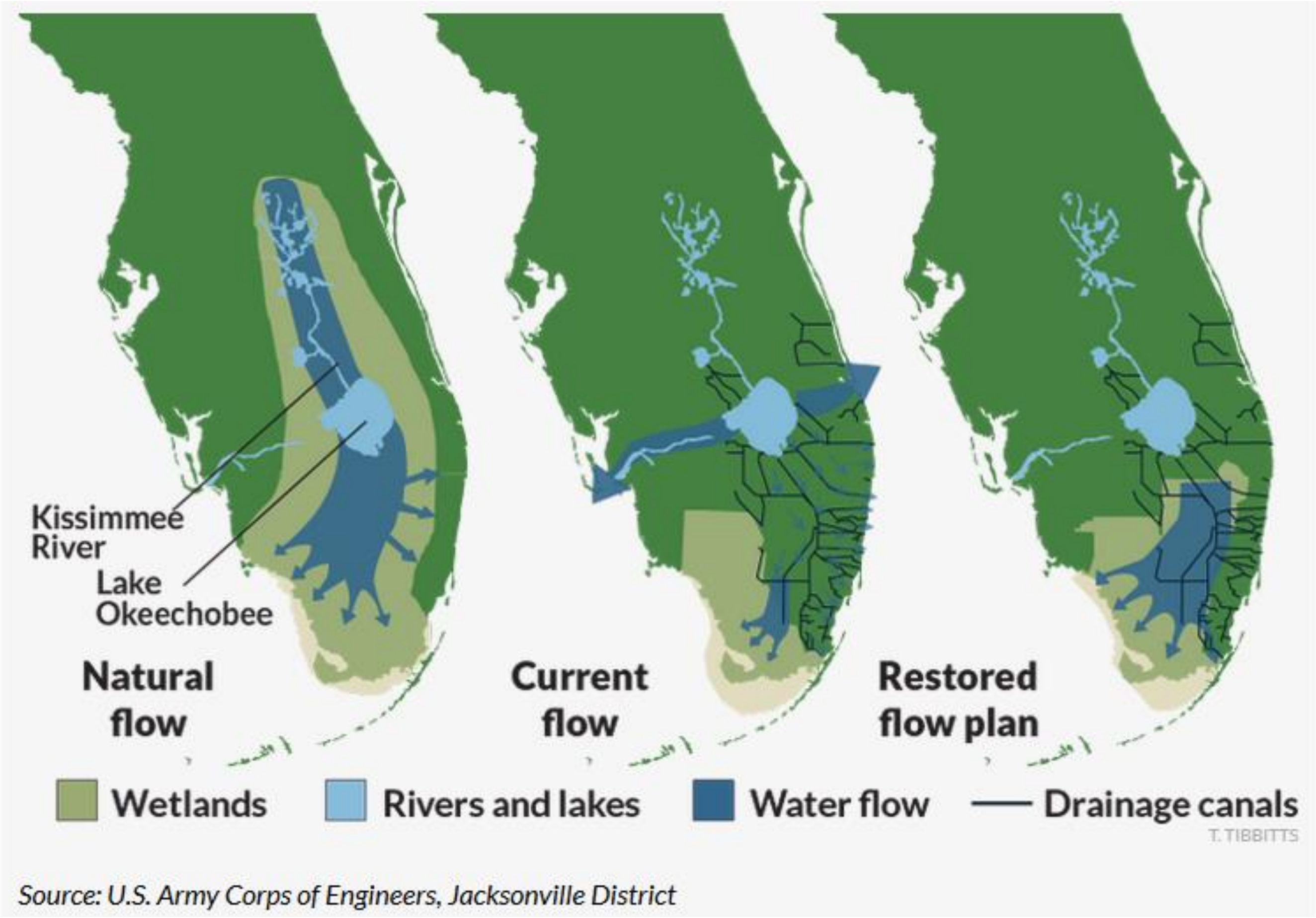
Outline:

- Everglades
- Shark River Slough
- Expanding to regional analysis
- Summary
- Conclusions

Everglades Freshwater Flow



- Highly managed freshwater delivery
- Amount and timing of delivery are equally important

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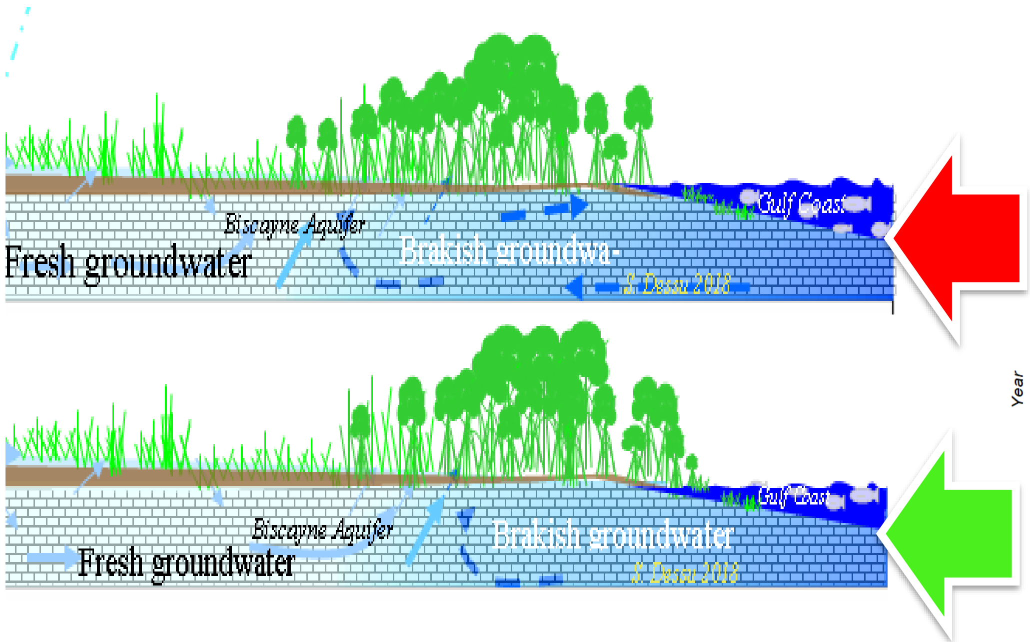
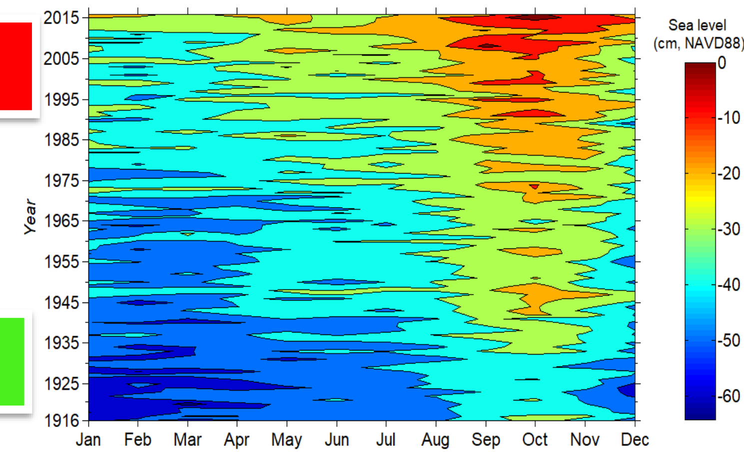
Everglades and Sea-level Rise



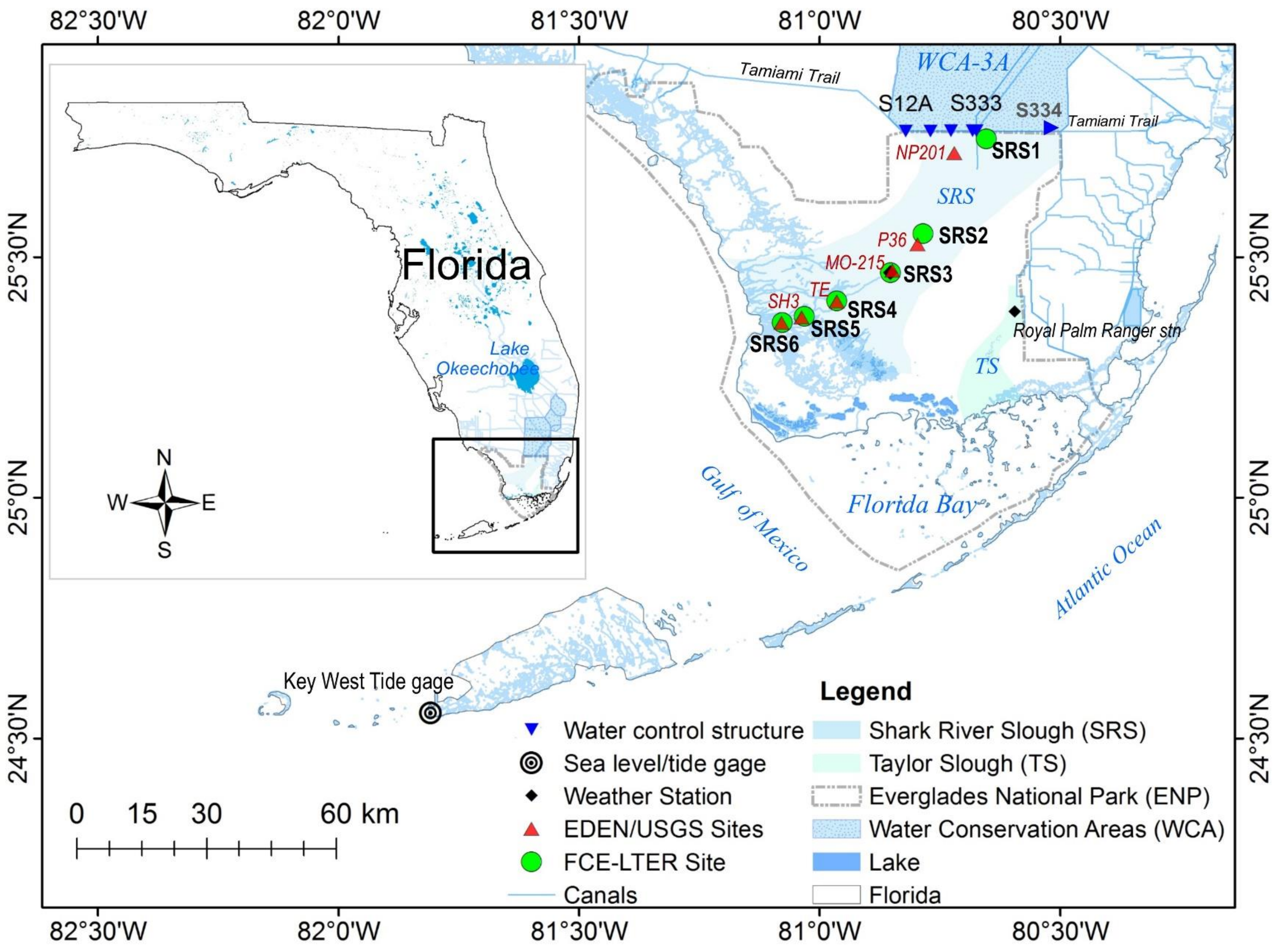
Coastal Everglades



Sea-level @Key west

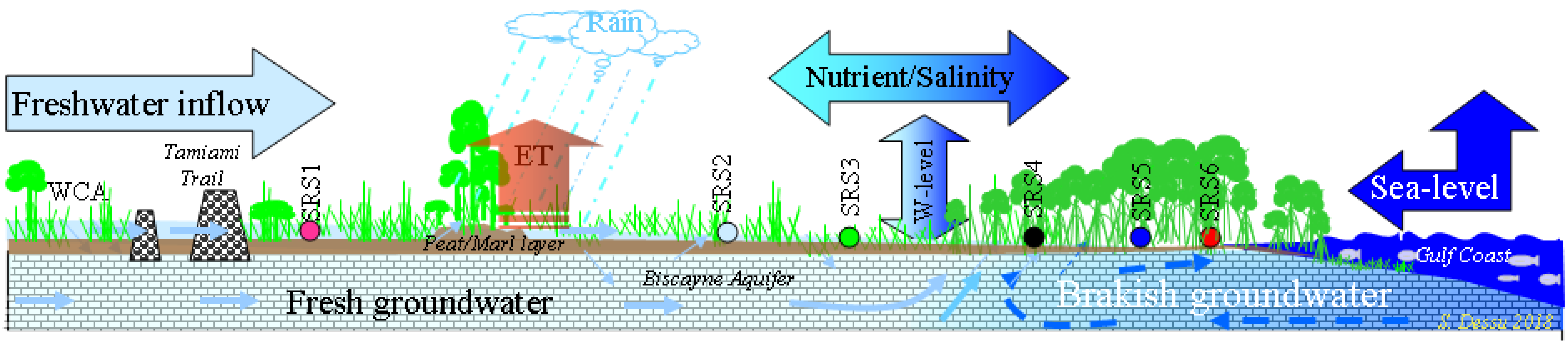
- Ecosystem composition and function depends on the fresh-marine water balance
- Sea-level rise is threatening coastal everglades

Shark River Slough



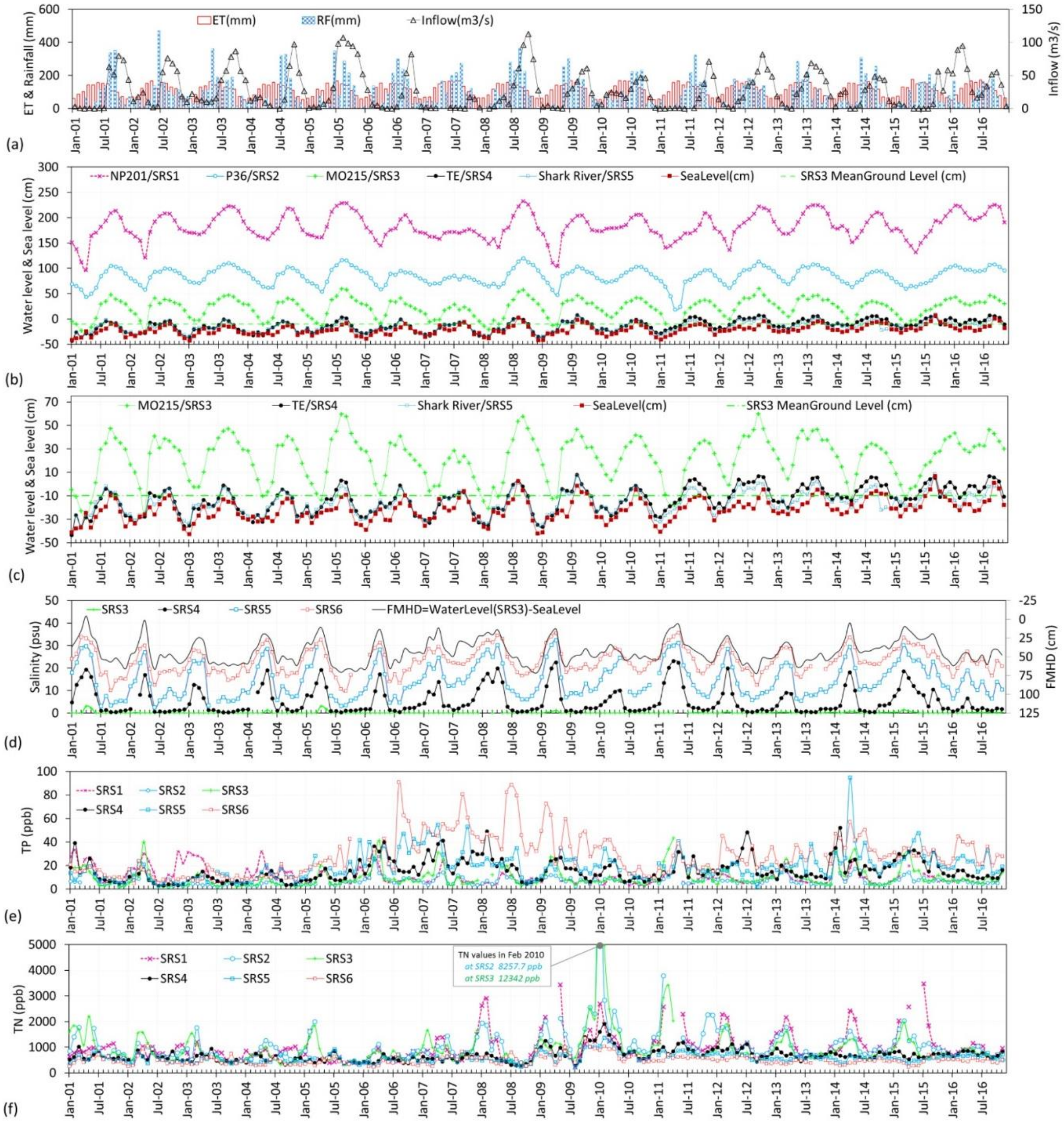
Objectives

- To determine how water levels, salinity and nutrients responded to upstream freshwater management and sea level rise
- To isolate the impact of freshwater inflows to counteract the adverse effects of SLR.



Data

- Hydrologic:
  - Inflow, Q
  - Rain, RF
  - ET
  - Sea-Level, SL
  - Water level, WL
  - ***FMHD (derived)***
- Salinity
- Nutrient:
  - Total Phosphorus, TP
  - Total Nitrogen, TN

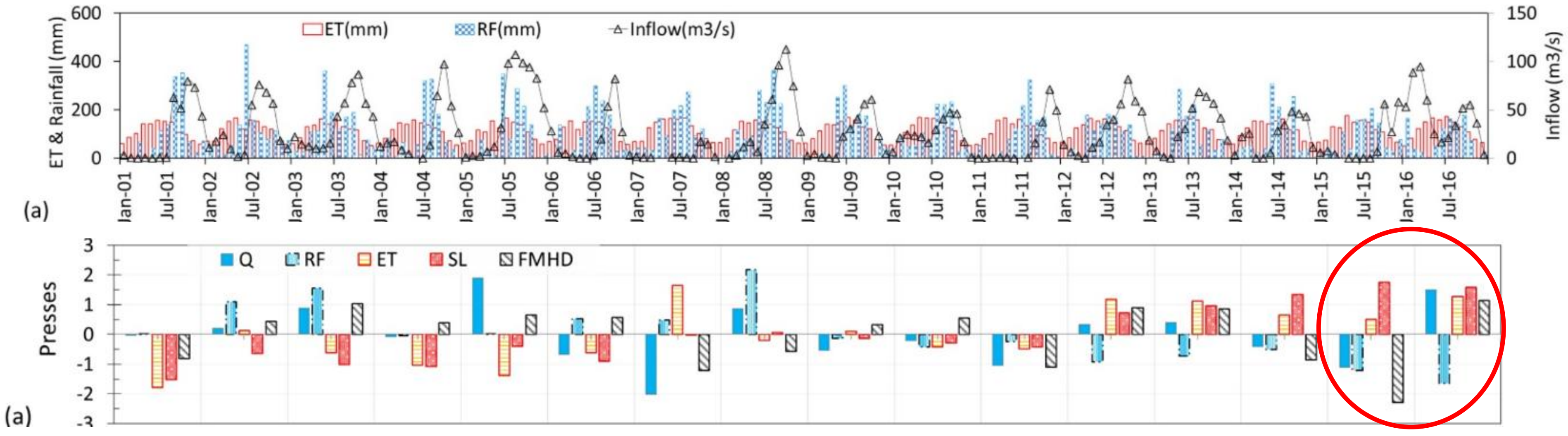


Data sources: SFWMD 2017; EDEN/USGS 2017; Harvey and McCormick 2008; Holgate et al. 2012; and Gaiser and Childers 2017)

Methods

- Data scaling (z-score): $Z(x) = \frac{x - \bar{x}}{\sigma_x}$
- Percent exceedance: $\%E(x_n) = \frac{n \times 100}{N+1}$
- Linear regression: $WL_{SRS4} = 0.31FMHD + 18.7;$ $r^2 = 0.76$

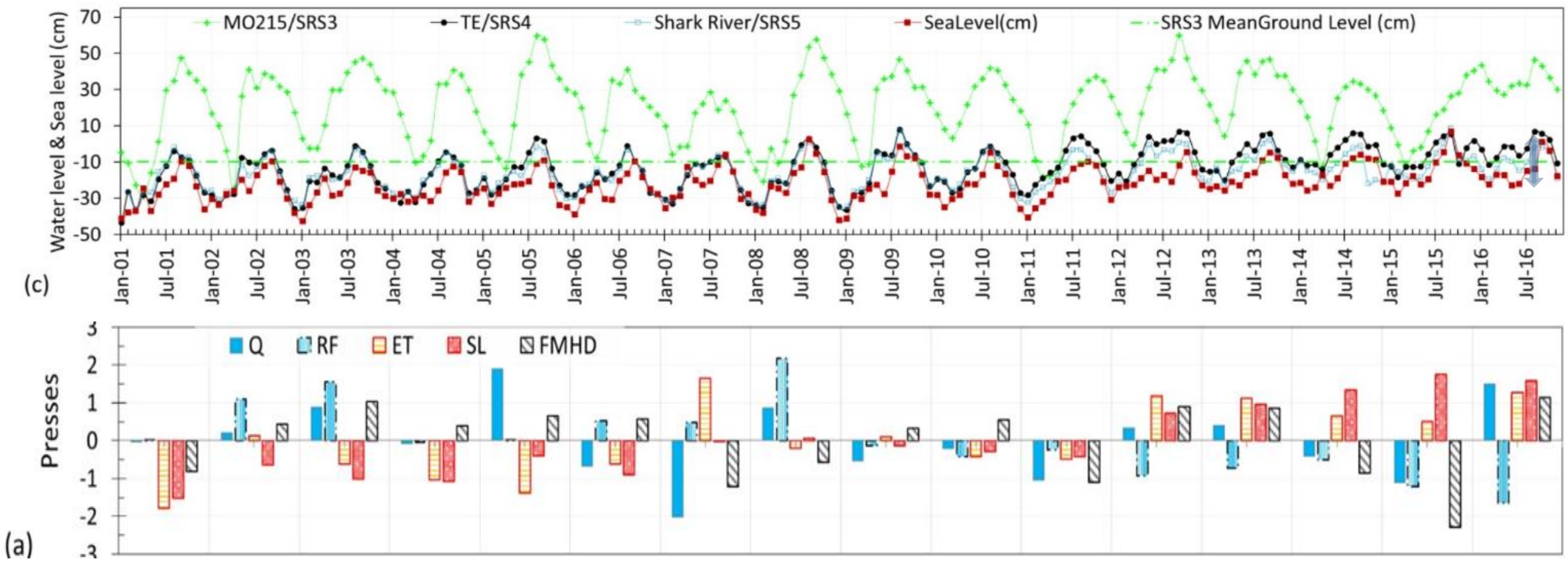
Annual Hydrologic Trend



- A slight decrease in rainfall and slight increase in ET
- Inflow was variable with the lowest in 2007
- Increasing trend of annual sea-level
- 2015 and 2016 are the lowest and highest FMHD years

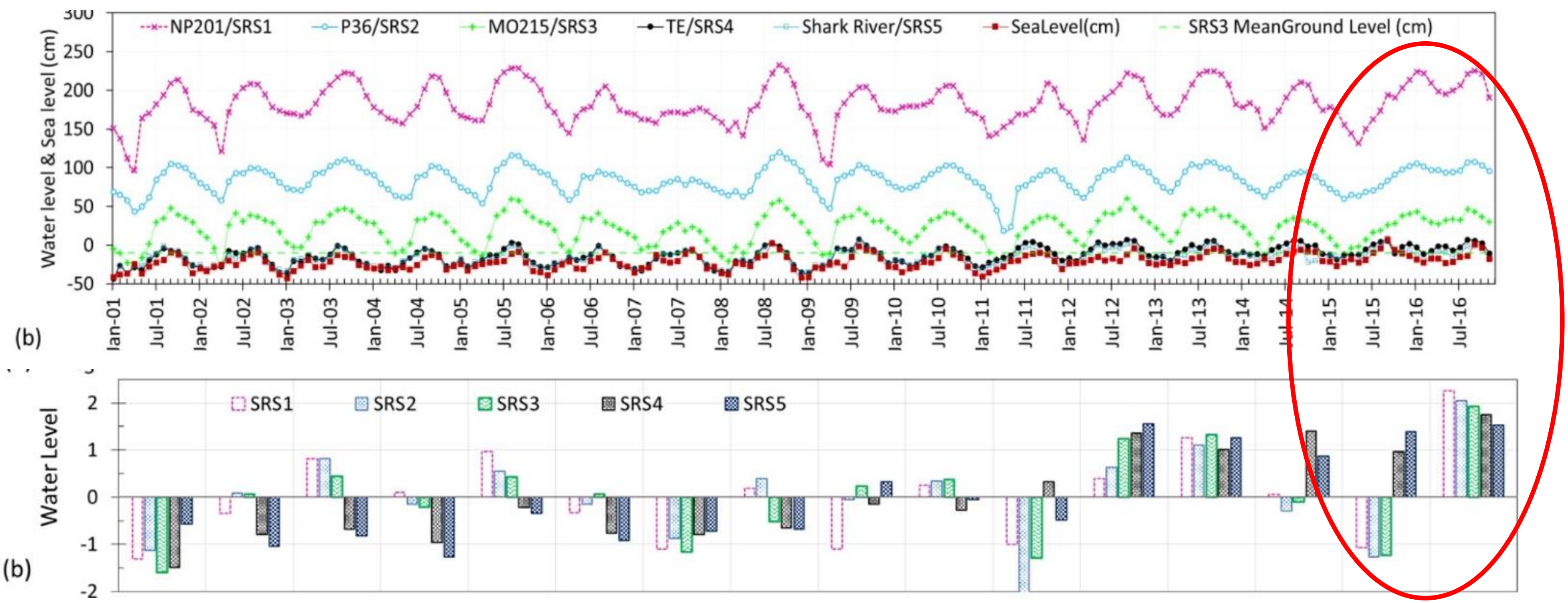
Data sources: SFWMD 2017; EDEN/USGS 2017; Harvey and McCormick 2008; Holgate et al. 2012; and Gaiser and Childers 2017)

Annual Hydrologic Trends



1. 13 cm increase in annual sea level from in 2001 to 2015.
2. ~10 cm increase in the lowest monthly sea level in the dry season
3. Increasing frequency of sea level above mean ground level at SRS3
4. decreasing seasonal and inter-monthly variability.
5. rising sea level trend with above average values since 2012.

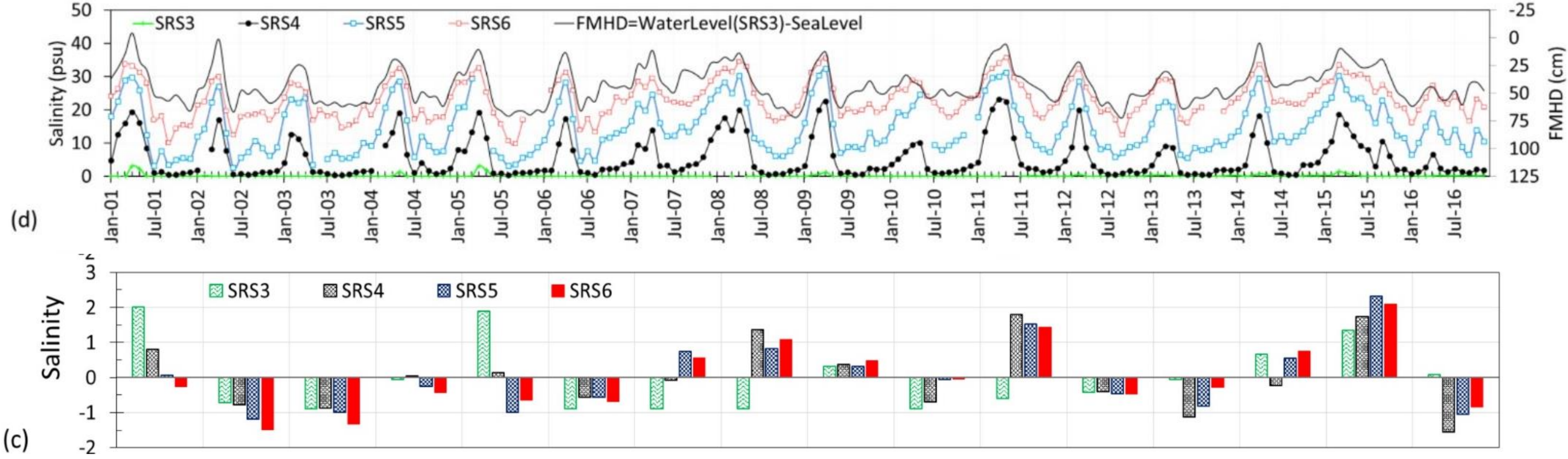
Annual Water Level Trends



- Annual average water level varied at freshwater sites
- Increasing water level trend at brackish sites
- largest difference between fresh and brackish sites in 2015
- Highest water level in 2016

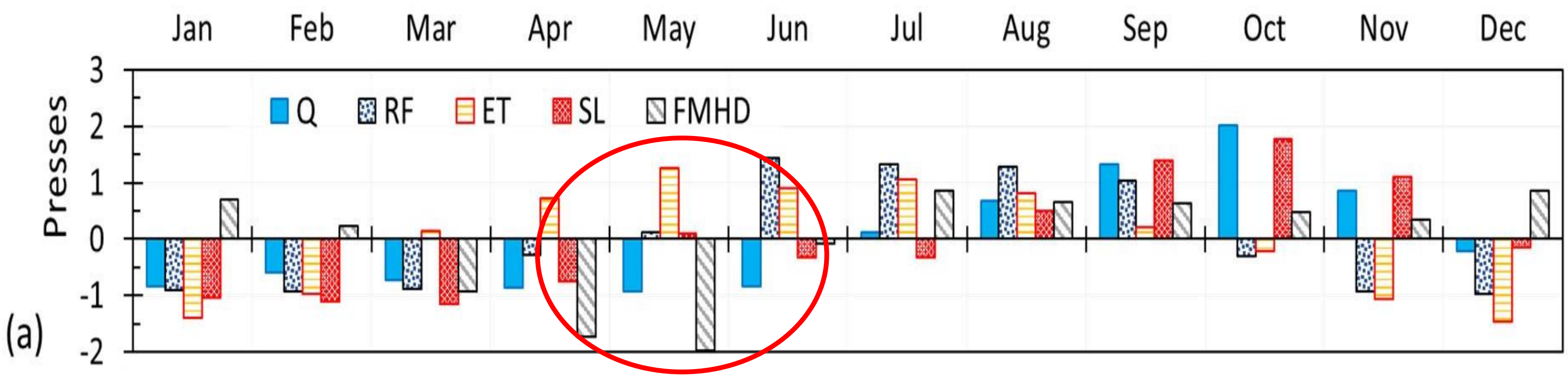
Data sources: SFWMD 2017; EDEN/USGS 2017; Harvey and McCormick 2008; Holgate et al. 2012; and Gaiser and Childers 2017)

Annual Salinity Trends



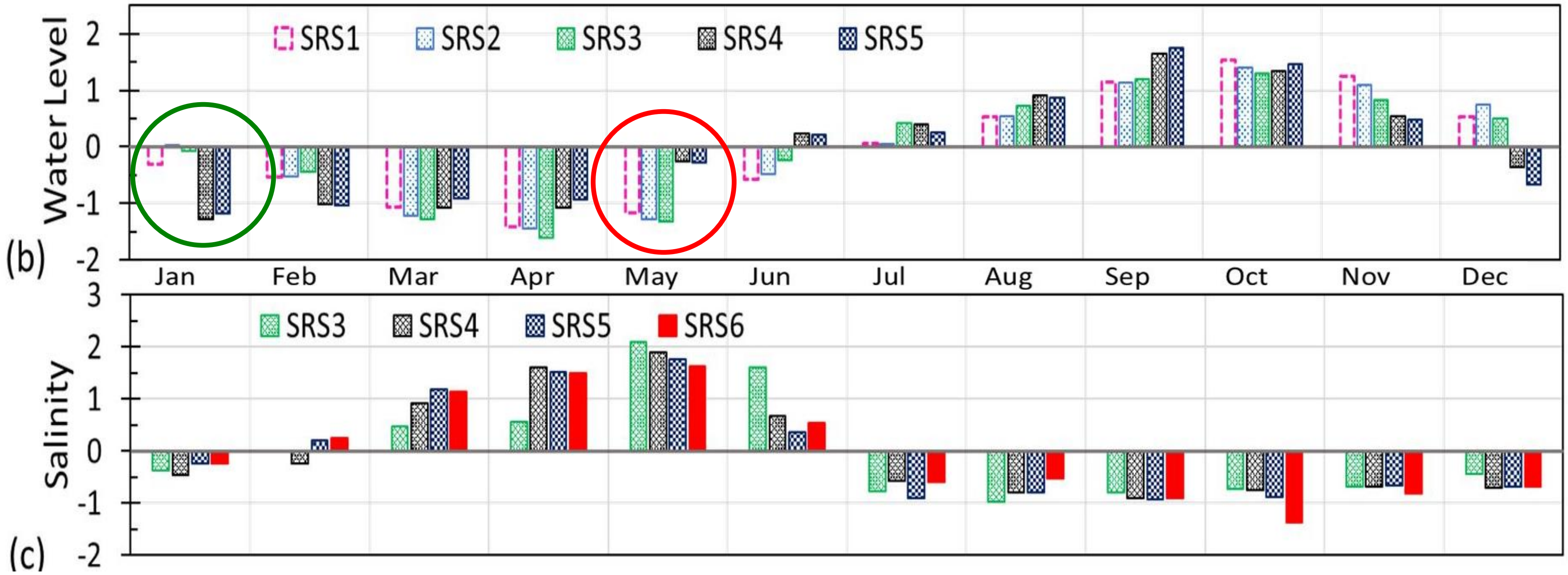
- Salinity increases towards the coast
- Monthly salinity varied inversely with FMHD
- Highest annual average salinity in 2015 followed by the lowest at SRS4 in 2016

Seasonal Hydrologic Trends



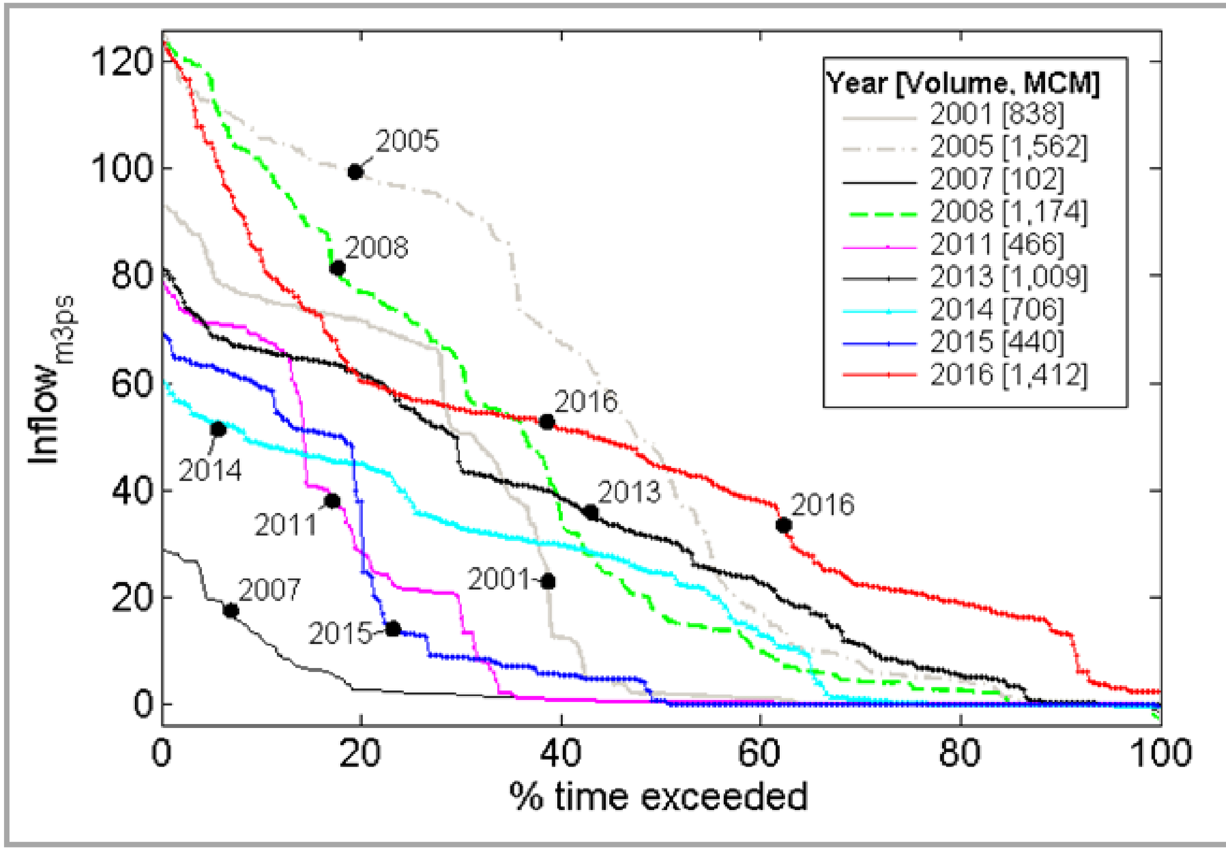
- Above average inflow from July to November (70% of the total)
- Above average rain from May to Sept
- Above average ET from March to Sept, two month earlier than rain
- **Above average sea level in May** and from August to November
- Below average FMHD is below average from March to May
- Lowest FMHD level in May
- Inflow and sea level followed same pattern except in May and July

Seasonal WL and Salinity Trends



- Water level and Salinity show seasonal variability with clear above and below average values
- Lower monthly variability in salinity from July to Dec.
- High difference between water levels in brackish and freshwater sites in January and May

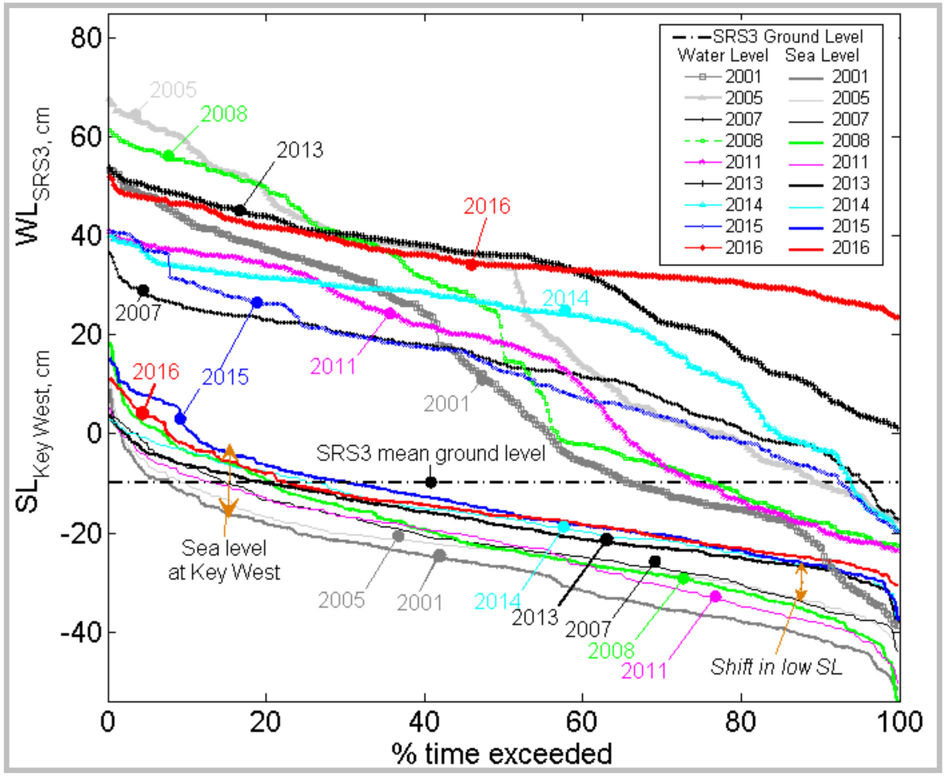
Inflow



- Annual inflow pattern and volume varied
- Hurricane/Storm years have steeper EC
- Least volume in 2007 and the highest in 2005/2016

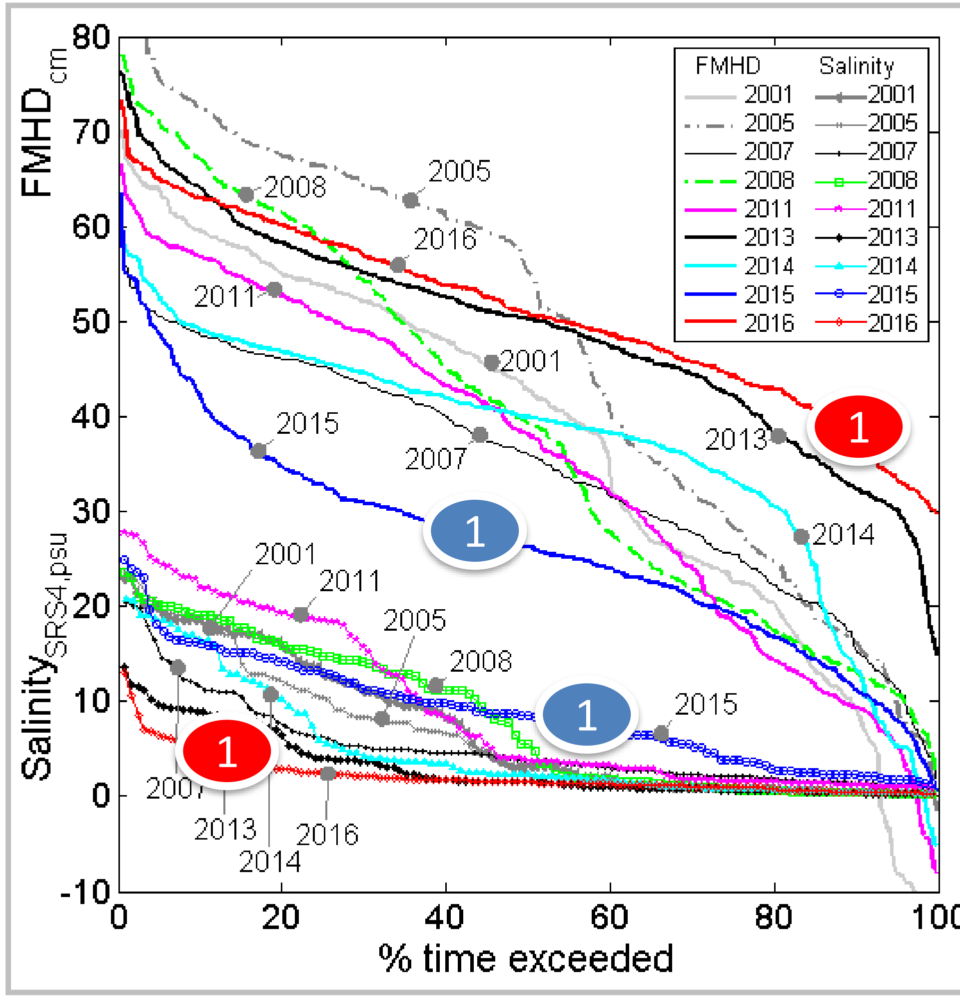
Water level (SRS3) & Sea-level

- Water levels at SRS3 varied by year
- Lower water levels displayed higher range
- WL in 2001 was below the average ground level ~35% of the year
- Seal-evel EC showed increasing trend
- Sea-level exceeded SRS3 ground elevation from 7% in 2001 to ~30% in 2015
- ~10cm shift in the lower sea level EC before and after 2011
- Sea-level rise decreasing the gap between WL(SRS3) and sea-level



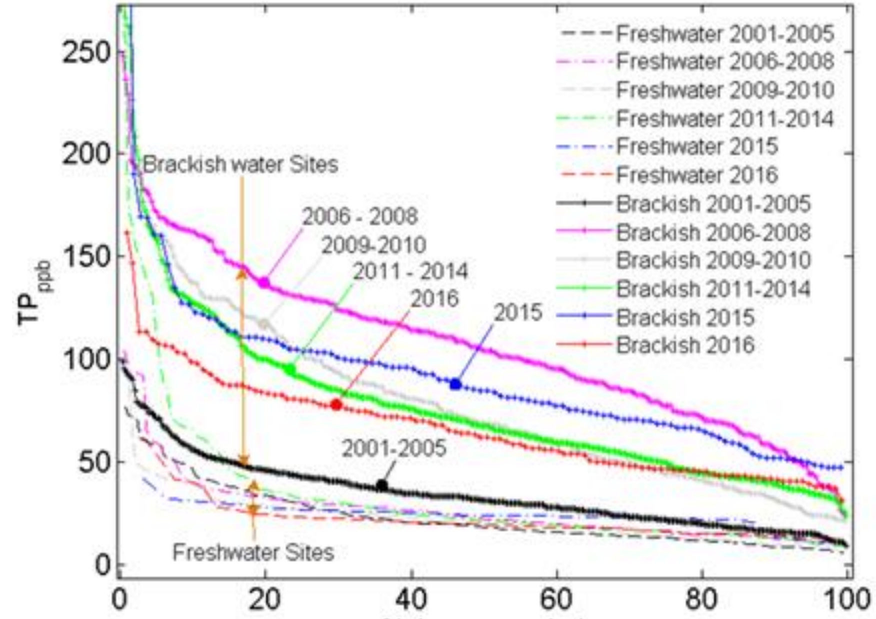
FMHD & Salinity

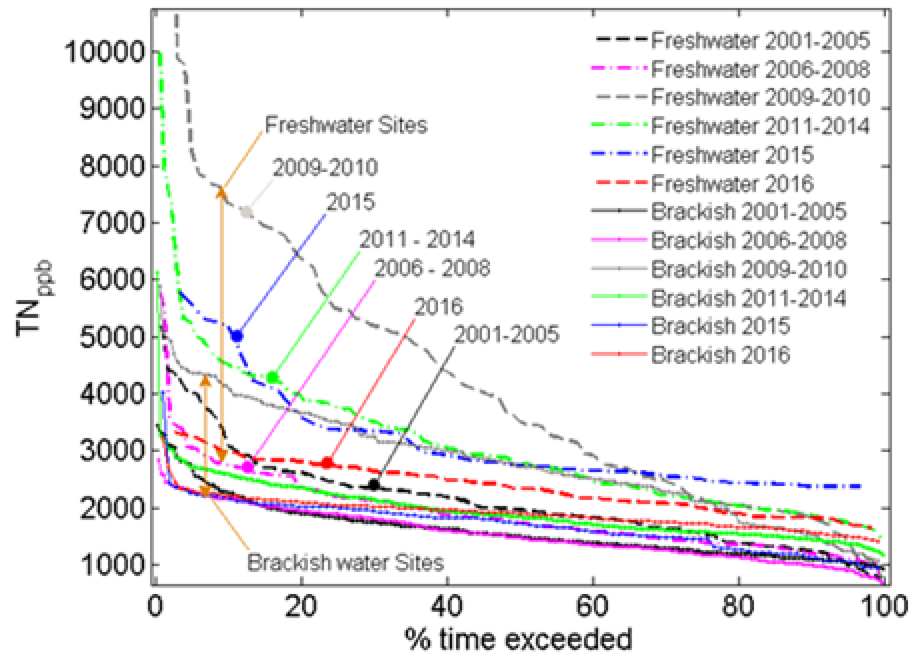
- **2015** and **2016** defined the lowest and highest FMHD of wet season and dry season, respectively
- Highest wet season salinity in **2015**, and lowest dry season salinity in **2016**
- The lowest FMHD in **2011** corresponded with the highest wet season salinity



TP & TN

- Lower TP and higher TN in freshwater marsh
- Higher range of variability in TP and TN in Brackish and freshwater marsh, respectively
- Extreme wet and dry years may have lasting impact on TP and TN





Linear Regression

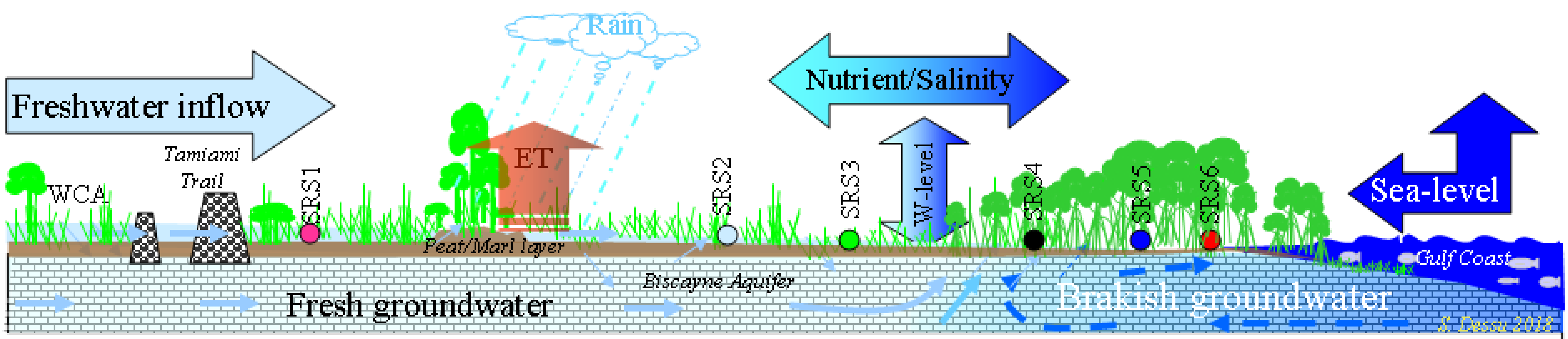
Table 2
Summary of regressions analysis and fitted regression model for response against press variables by site. Bold R^2 represents $p < .05$. Multiple linear regression models were selected based on largest R^2, lowest root mean square error (RMSE), p-value of the fitted model and individual coefficients, and visual comparison of observed and predicted model.

	R^2 for single Variable regression						Fitted regression model			
	Site	Q	ET	RF	SL	FMHD	Equation	R^2	RMSE	DF
WL	SRS1	**0.67**	**0.05**	0	NA	NA	$0.73Q - 0.14ET + 179.7$	**0.71**	13.7	189
	SRS2	**0.57**	**0.11**	0	NA	NA	$0.44Q - 0.12ET + 86.9$	**0.64**	10.2	189
	SRS3	**0.57**	**0.07**	0.01	**0.31**	NA	$0.41Q - 0.18ET + 0.05RF + 0.43SL + 35.6$	**0.68**	10.9	187
	SRS4	**0.31**	**0.04**	**0.12**	**0.76**	NA	$0.05Q + 0.15ET + 0.023RF + 0.92SL + 0.8$	**0.81**	5.02	186
	SRS5	**0.3**	**0.05**	**0.13**	**0.76**	NA	$0.04Q + 0.22ET + 0.02RF + 0.77SL - 5$	**0.83**	3.91	185
Salinity	SRS3	**0.05**	**0.04**	0	**0.01**	**0.21**	$-0.013FMHD + 0.69$	**0.21**	0.38	185
	SRS4	**0.3**	**0.17**	0	**0.1**	**0.76**	$-0.31FMHD + 18.7$	**0.76**	2.85	188
	SRS5	**0.44**	**0.12**	0	**0.11**	**0.82**	$-0.43FMHD + 33.0$	**0.82**	3.19	185
	SRS6	**0.49**	**0.13**	0	**0.12**	**0.78**	$-0.31FMHD + 36.5$	**0.78**	2.66	185
TP	SRS1	**0.11**	0.02	0	NA	NA	$-0.83Q + 12.59$	**0.11**	6.59	180
	SRS2	**0.06**	**0.04**	0.01	NA	NA	$-0.035Q + 0.21ET + 5.5$	**0.08**	4.0	181
	SRS3	**0.15**	**0.15**	0.01	**0.02**	**0.4**	$-0.32FMHD + 23.5$	**0.40**	6.1	184
	SRS4	**0.13**	**0.09**	0.02	**0.01**	**0.2**	$-0.27FMHD + 27.6$	**0.20**	8.7	188
	SRS5	**0.04**	**0.07**	0.01	**0.01**	**0.14**	$-0.29FMHD + 32.0$	**0.14**	11.1	185
	SRS6	0	**0.02**	0.01	**0.03**	**0.02**	$-0.16FMHD + 35.1$	**0.02**	17.0	185
TN	SRS1	**0.15**	0.02	0	NA	NA	$-7.65Q + 1200$	**0.14**	529	180
	SRS2	**0.09**	0	0.01	NA	NA	$-7.89Q + 1268$	**0.09**	720	181
	SRS3	**0.06**	0	0.01	**0.06**	**0.07**	$-8.89Q + 1219$	**0.06**	983	185
	SRS4	**0.07**	0	0.01	**0.02**	0.02	$-2.21Q + 735$	**0.06**	236	188
	SRS5	0	0.01	0	0	0	Models rejected ($p > .05$)			
	SRS6	0	0.01	0.02	0.01	0.01	Models rejected ($p > .05$)			

- Inflow explained > 50% of variability in freshwater marsh WL
- Sea level explained >75% of variability brackish marsh WL
- FMHD explained > 75% of variability in salinity
- FMHD performed better in capturing TP in brackish water marsh

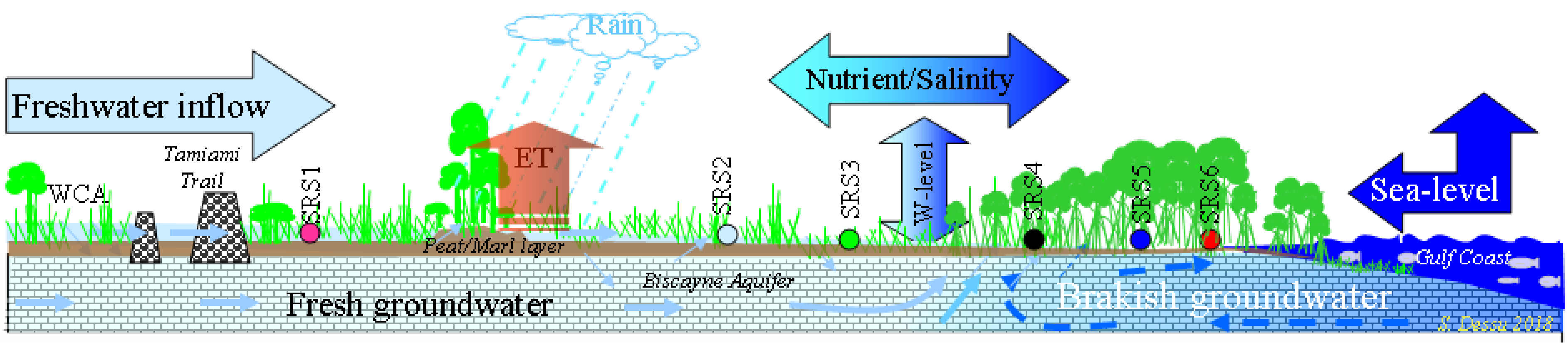
Freshwater Delivery

- Annual Rainfall and ET are almost equivalent
- Freshwater delivery is key to maintain freshwater level and push-back salinity
- Timing of freshwater delivery is critical to match with sea level pattern
- Time and amount of delivery are equally important
- Existing delivery schedules may need to be revised to meet current conditions



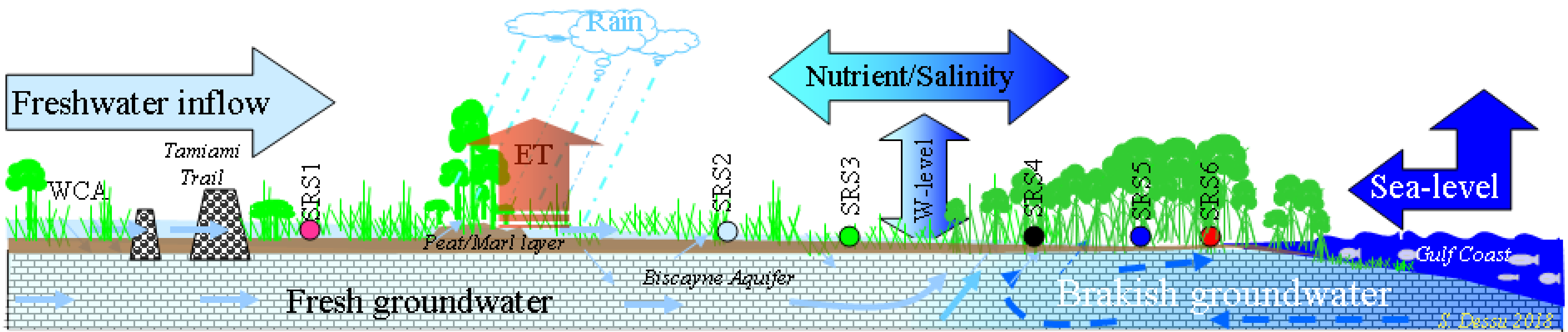
Sea-level

- The dry season is experiencing higher sea level
- Seasonal sea level range is decreasing
- The above average sea level is May happens when there is practically no freshwater delivery
- More freshwater marsh areas are being exposed to sea water



Conclusions

- The water level, salinity and nutrient responses of SRS varied with time scales from monthly to long-term.
- Delayed rainfall or inflow exacerbates salinity during the dry season
- Freshwater delivered earlier in the dry season can have a higher impact in reducing salinity than high inflow pulses after peak salinity
- Coastal everglades is likely to continue in a transient state adjusting to sea level rise
- FMHD can help to bridge freshwater management with SLR



Way Forward

- Lessons learned from this study in SRS:
  - Long-term data synthesis requires robust tools
  - Increasing type and volume of long-term data
  - Synthesis tools are essential to match the need, and
  - Expand the study to cover Taylor slough, Florida Bay and Biscayne Bay
- A new tool (PRIME) is developed and currently being used for a similar study in Taylor Slough and Florida Bay
- Integration of surface and groundwater flow patterns with sea level rise is being done over a 37km transect in Taylor Slough

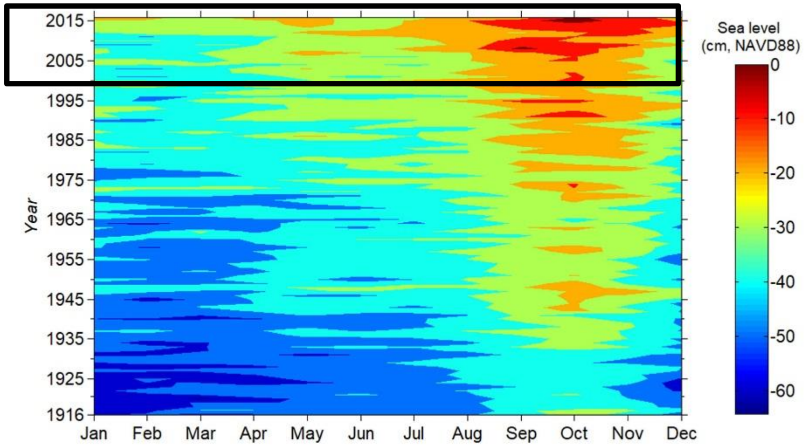
Part II

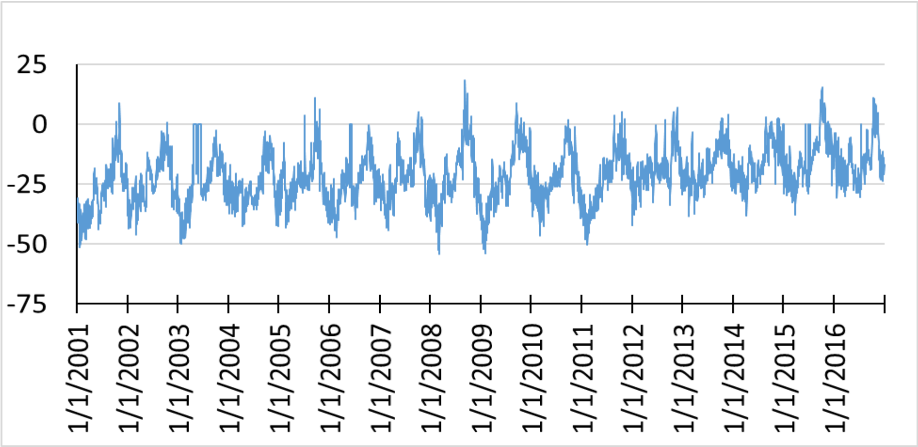
PRIME

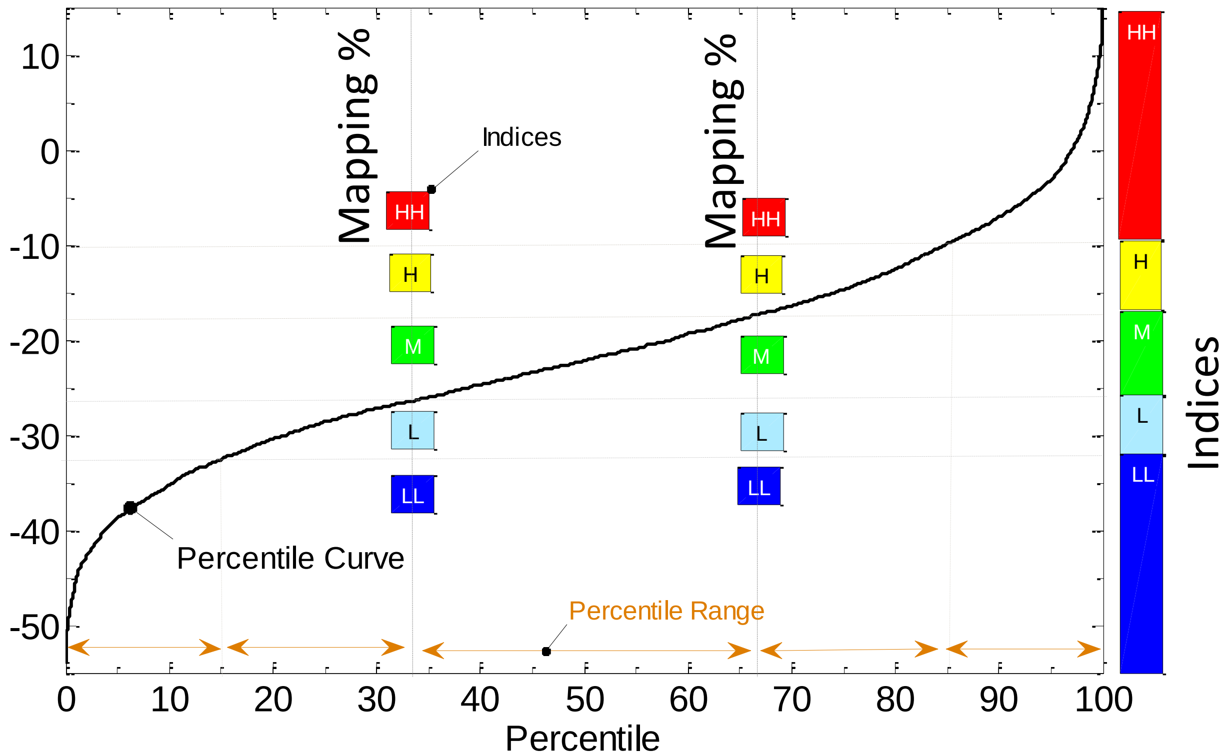
Percentile Range Indexed Mapping and Evaluation

(Dessu et al. 2018c)

PRIME: Percentiles, Range and Indices

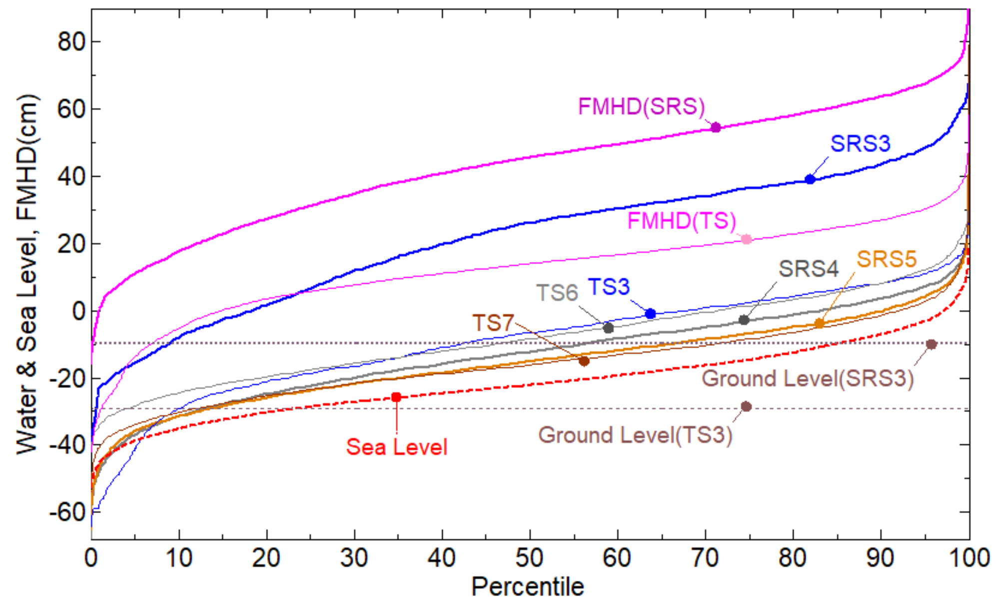


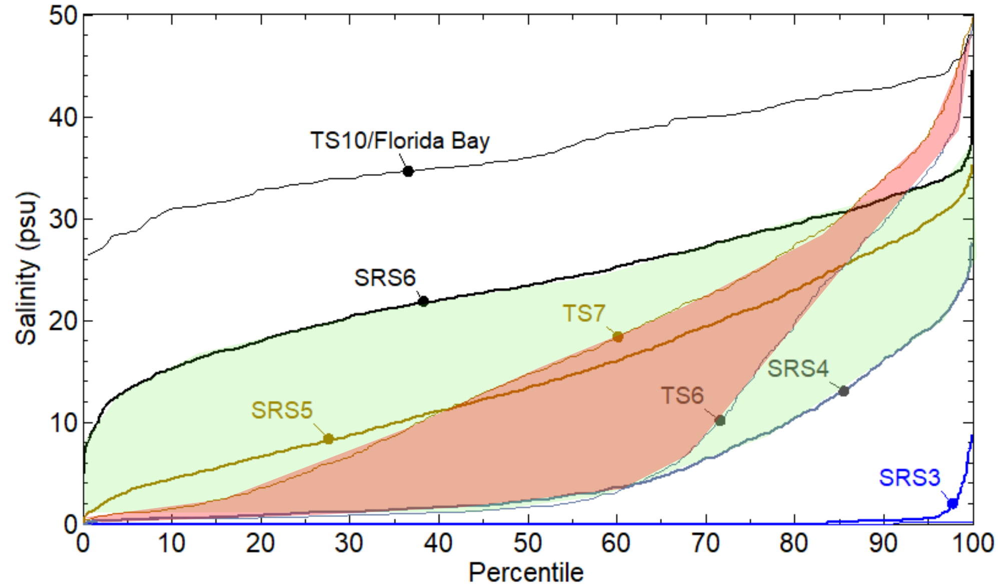




FCE: Long-term signature

- Water level
  - SRS, TS, Sea level, FMHD and Ground elevations
- Salinity
  - SRS, Taylor Slough and Florida Bay exhibited distinct patterns





FCE: cross-site seasonal status map

- Clear seasonal trend
- Lag of two-thre months between fresh and salt water marshes
- FMHD mirrors salinity

Variable	Site	33rd percentile												67th percentile											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Water Level	SRS1	L	L	LL	LL	LL	L	M	M	H	H	H	M	M	M	L	L	L	M	M	H	H	HH	HH	H
	SRS2	M	L	L	LL	LL	LL	M	M	H	H	H	M	M	M	L	L	L	M	M	H	HH	HH	HH	H
	SRS3	M	L	L	LL	LL	L	M	M	H	H	M	M	M	M	L	L	L	M	H	H	HH	HH	H	H
	SRS4	LL	LL	L	L	L	M	M	M	H	H	M	L	M	M	L	M	M	M	H	H	HH	HH	H	M
	SRS5	LL	LL	L	L	L	M	M	M	H	H	M	L	M	M	M	M	M	M	H	H	HH	HH	H	M
	TS2	L	L	LL	LL	LL	M	M	H	H	H	M	M	M	L	L	L	M	M	H	HH	HH	HH	H	H
	TS3	L	L	L	LL	LL	L	M	M	H	H	M	M	M	M	L	L	L	M	H	H	HH	HH	H	M
	TS6	LL	LL	LL	L	L	M	M	M	H	H	M	L	L	M	L	L	M	M	H	H	HH	HH	H	M
	TS7	LL	LL	LL	L	L	M	M	M	H	H	M	L	L	M	L	M	M	M	M	H	HH	HH	H	M
Sea level	Kwest	LL	LL	LL	L	M	M	L	M	H	H	H	L	M	M	L	M	M	M	M	H	HH	HH	HH	M
FMHD	SRS	M	M	L	LL	LL	L	M	M	M	M	M	M	H	M	M	L	LL	M	H	H	H	H	H	H
	TS	M	M	L	LL	LL	LL	M	M	M	M	M	M	H	H	M	L	L	H	H	H	H	M	M	H

(a)

Variable	Site	33rd percentile												67th percentile											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Salinity	SRS4	M	M	H	H	H	M	L	L	LL	LL	L	M	M	M	H	HH	HH	HH	M	M	L	L	M	M
	SRS5	M	M	H	H	H	M	L	L	L	L	L	L	M	H	H	HH	HH	H	M	M	M	M	M	M
	SRS6	L	M	M	H	H	M	L	L	L	LL	L	L	M	M	H	HH	HH	H	M	M	M	L	M	M
	TS6	L	L	M	H	H	H	M	M	L	L	L	L	M	M	H	HH	HH	HH	H	M	M	M	M	M
	TS7	L	M	M	H	H	M	L	L	LL	LL	L	L	M	M	H	H	HH	HH	H	M	M	L	M	M
	TS9	LL	L	M	M	M	M	M	M	L	L	L	M	M	M	HH	M	H	H	H	M	M	M	H	M
	TS10	L	L	L	M	M	M	M	L	L	L	LL	L	M	M	M	H	HH	H	H	H	M	M	M	M
	TS11	LL	L	L	M	M	M	M	L	M	M	L	LL	L	M	M	H	H	HH	H	M	M	H	M	M

(b)

FCE: Cross-site annual status map

- Water levels and sea level increased gradually
- FMHD varied across the 16 years

(c)

Variable	Site	33rd Percentile															
		2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Water Level	SRS1	LL	L	M	L	L	M	L	L	L	M	L	M	M	M	L	H
	SRS2	LL	M	M	L	L	M	L	L	M	M	L	M	M	M	L	H
	SRS3	LL	M	L	L	L	M	L	LL	M	M	LL	M	M	M	L	M
	SRS4	LL	L	L	L	L	L	L	L	L	L	M	M	M	M	M	M
	SRS5	L	L	L	L	L	L	L	L	L	M	L	M	M	M	M	M
	TS2	L	L	M	L	L	L	L	L	M	M	LL	M	M	M	L	H
	TS3	LL	M	M	L	L	L	L	L	L	M	L	M	M	M	M	M
	TS6	LL	L	M	L	L	L	L	L	L	M	L	M	M	M	M	M
	TS7	L	L	L	L	M	L	L	L	L	L	L	M	M	M	M	M
Sea Level	Kwest	LL	L	L	L	L	L	L	L	L	L	L	M	M	M	M	M
FMHD	SRS	L	M	M	M	L	M	L	L	M	M	L	M	M	L	LL	M
	TS	L	M	M	L	L	L	L	L	L	M	L	M	M	L	L	M

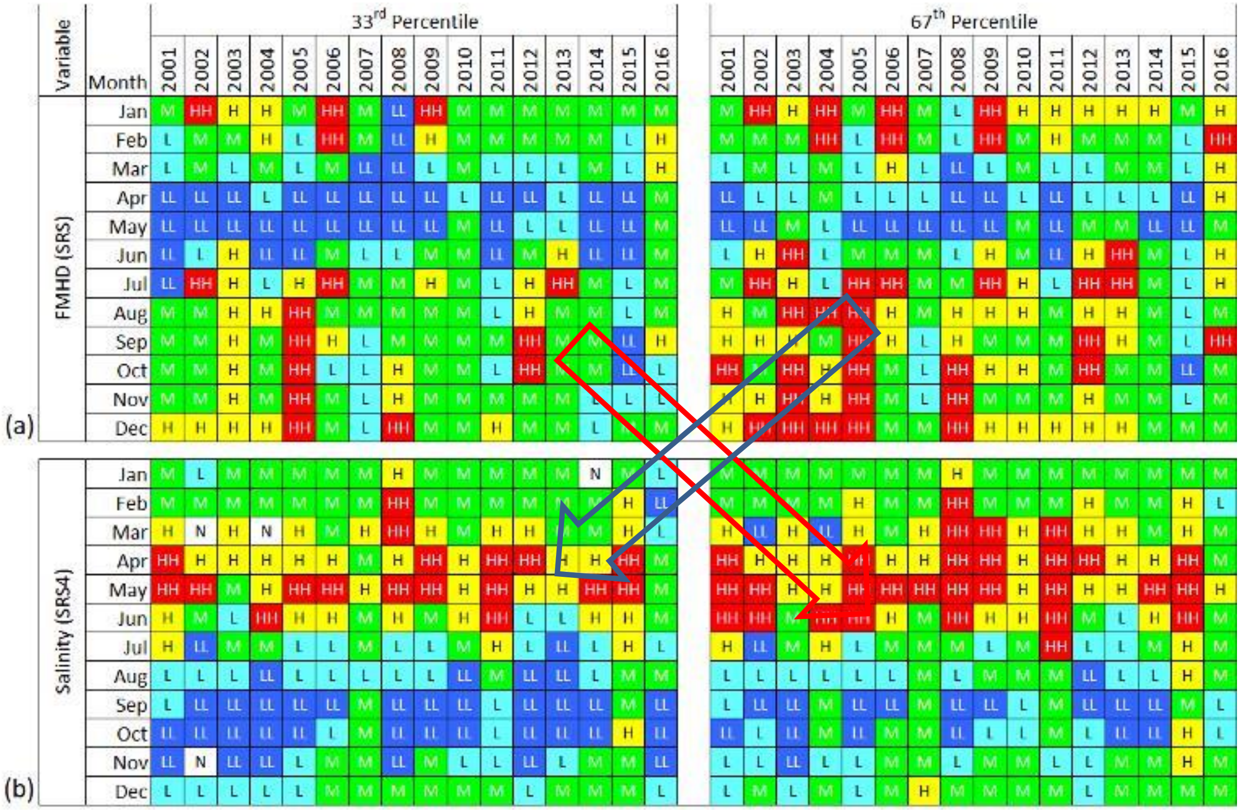
Variable	Site	67th Percentile															
		2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Water Level	SRS1	M	M	H	M	HH	M	M	H	M	M	M	H	HH	M	M	HH
	SRS2	M	M	H	M	HH	M	M	HH	M	M	M	H	H	M	M	HH
	SRS3	M	H	H	M	H	M	M	H	H	M	M	H	H	M	M	H
	SRS4	M	M	M	M	M	M	M	M	H	M	H	HH	H	H	H	HH
	SRS5	H	M	M	M	M	M	M	H	H	M	M	H	H	H	H	H
	TS2	H	M	H	M	H	M	M	H	H	M	M	HH	H	M	M	HH
	TS3	M	M	M	M	M	M	M	M	M	M	M	HH	H	H	H	H
	TS6	M	H	M	M	M	M	M	M	H	M	M	H	H	H	H	H
	TS7	M	M	M	M	M	M	H	H	H	M	M	H	H	H	HH	H
Sea Level	Kwest	M	M	M	M	M	M	M	H	H	M	M	H	H	H	H	H
FMHD	SRS	M	H	H	H	HH	H	M	M	H	M	M	H	H	M	L	H
	TS	M	H	H	M	H	H	M	M	H	H	M	H	M	M	M	H

(d)

Variable	Site	33rd Percentile															
		2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Salinity	SRS4	L	L	L	L	L	M	M	M	M	M	M	L	L	L	H	L
	SRS5	L	L	LL	L	LL	L	M	L	L	M	M	L	L	M	H	L
	SRS6	L	L	L	L	L	L	M	M	M	M	M	L	L	M	H	L
	TS6	L	L	LL	M	M	M	M	M	M	L	M	L	L	M	H	L
	TS7	L	LL	LL	M	M	M	L	M	M	M	M	L	L	M	H	L
	TS9	LL	LL	L	M	M	M	L	M	M	L	L	LL	L	M	H	N
	TS10	M	LL	L	M	M	M	L	L	M	M	L	LL	L	M	M	N
	TS11	M	LL	L	L	L	L	M	M	H	LL	L	L	M	L	M	N

Variable	Site	67th Percentile															
		2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Salinity	SRS4	H	M	M	M	H	M	M	HH	M	M	HH	M	M	M	H	M
	SRS5	H	M	M	M	M	M	H	H	M	M	HH	M	M	H	H	M
	SRS6	M	M	M	M	H	M	M	HH	H	M	HH	M	H	M	H	M
	TS6	H	M	L	H	H	M	M	HH	M	M	H	H	M	M	HH	M
	TS7	M	M	L	H	HH	H	H	H	H	M	H	M	M	H	HH	M
	TS9	M	L	M	H	HH	M	M	H	M	M	H	M	M	H	HH	N
	TS10	H	L	M	H	HH	H	M	M	H	M	H	L	M	H	H	N
	TS11	M	M	M	M	M	M	H	HH	HH	M	H	M	M	M	HH	N

FCE: FMHD vs. Salinity (SRS)



67th Salinity (columns) vs. **33rd FMHD** (rows)

33rd FMHD	LL	L	M	H	HH
LL	0	0	*1*	***12***	***24***
L	0	1	***11***	***18***	***5***
M	*10*	***17***	***44***	**7**	*0*
H	***6***	***11***	**10**	0	0
HH	***4***	***5***	*6*	0	0

33rd Salinity (columns) vs. **67th FMHD** (rows)

67th FMHD	LL	L	M	H	HH
LL	0	0	*0*	***3***	**15**
L	0	0	***9***	***23***	***3***
M	*9*	**12**	**28**	**9**	*0*
H	***14***	***11***	**17**	0	0
HH	***14***	***14***	*7*	0	0

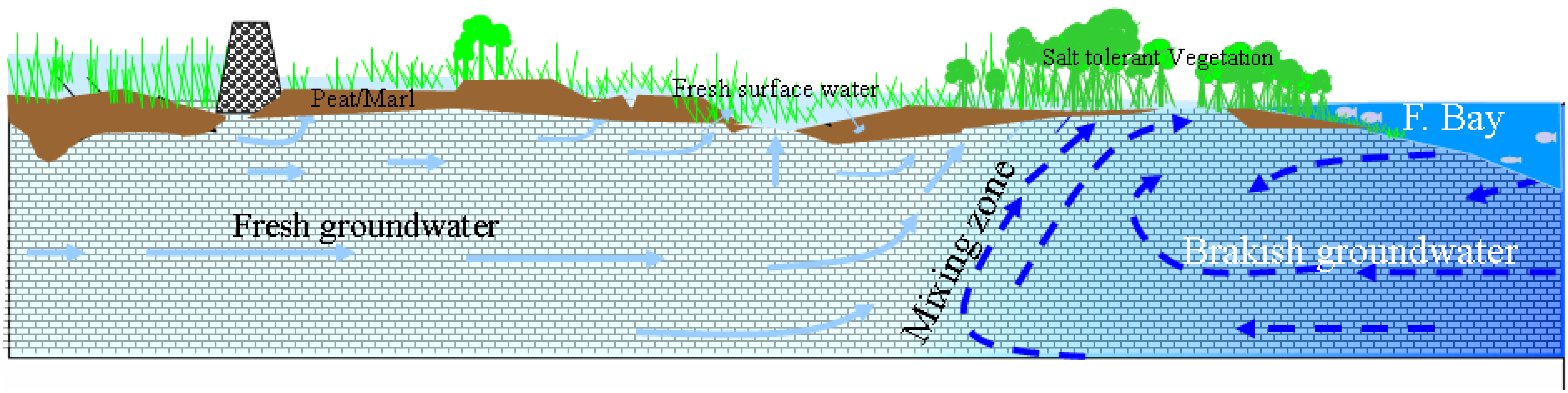
Relationship: Contingency Table

Map 1			Map 2			Summary Statistics			
						% of Total Count			
Variable	Site	at %le	Variable	Site	at %le	Diagonal	Diagonal Band	Total Count	* Chi-square
Salinity	SRS4	33	WL	SRS3	67	67.6	99.5	188	318.8
		67			33	65.6	96.9	192	273.3
		33	Sea level	KW	67	36.2	73.9	188	77.9
		67			33	31.8	75.0	192	48.0
		33	FMHD	SRS	67	48.4	91.5	188	225.9
		67			33	52.6	90.6	192	170.2
Salinity	TS6	33	WL	TS3	67	34.1	90.3	185	125.6
		67			33	47.1	89.9	189	129.8
		33	Sea level	KW	33	30.3	68.6	185	27.5
		67			67	25.4	67.7	189	24.2
		33	FMHD	TS	67	41.6	87.6	185	156.9
		67			33	46.6	86.8	189	124.1
Water level	SRS3	33	Sea level	KW	33	37.0	80.2	192	79.5
		67			67	38.0	77.6	192	72.5
	TS3	33	Sea level	KW	33	40.6	86.5	192	109.2
		67			67	39.6	82.3	192	114.7

***P-value < 0.05 for all chi-square test**

Part III

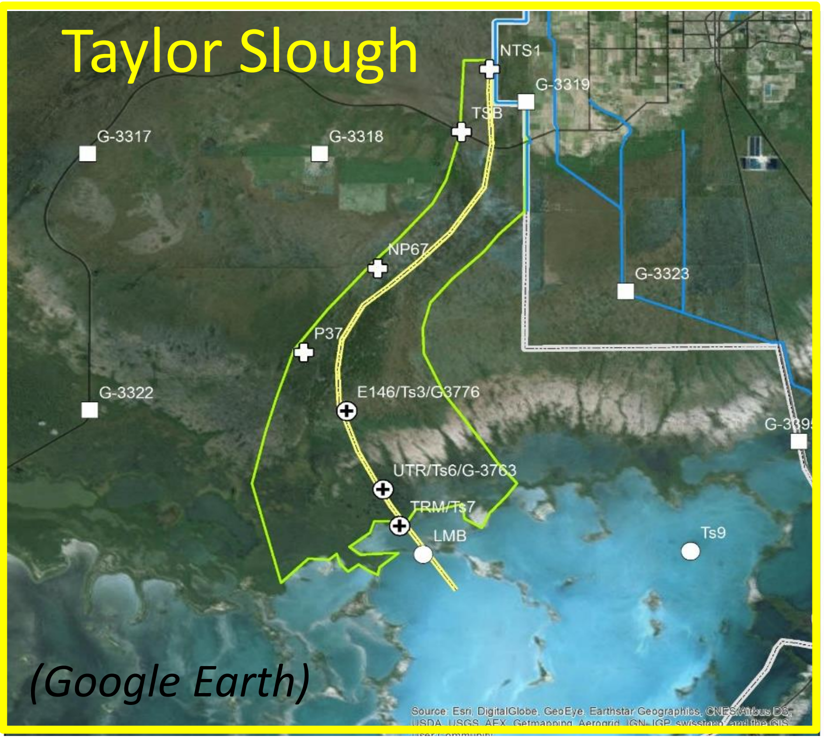
Groundwater Flow Pattern in Taylor Slough

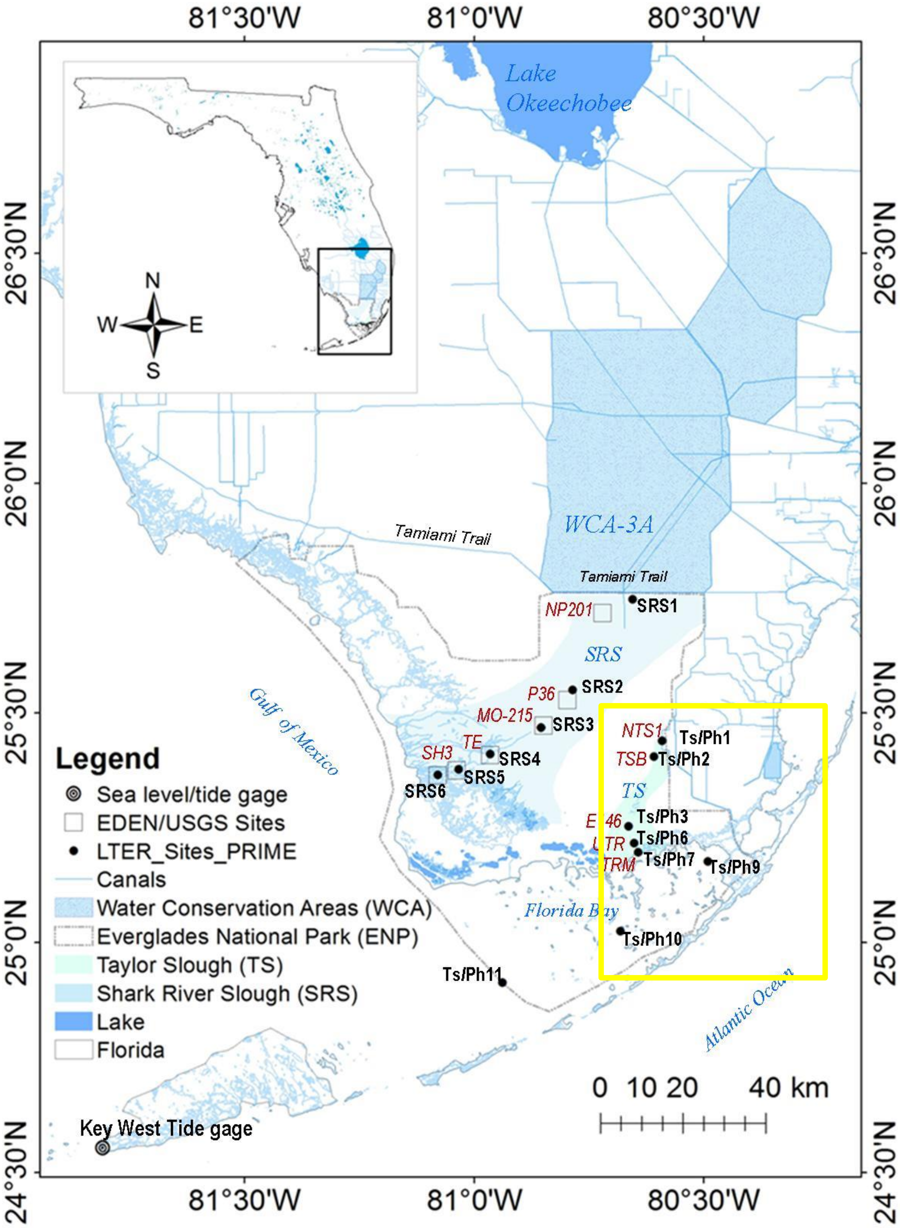


(Dessu and Price 2017, 2018)

Groundwater Flow Pattern in Taylor Slough

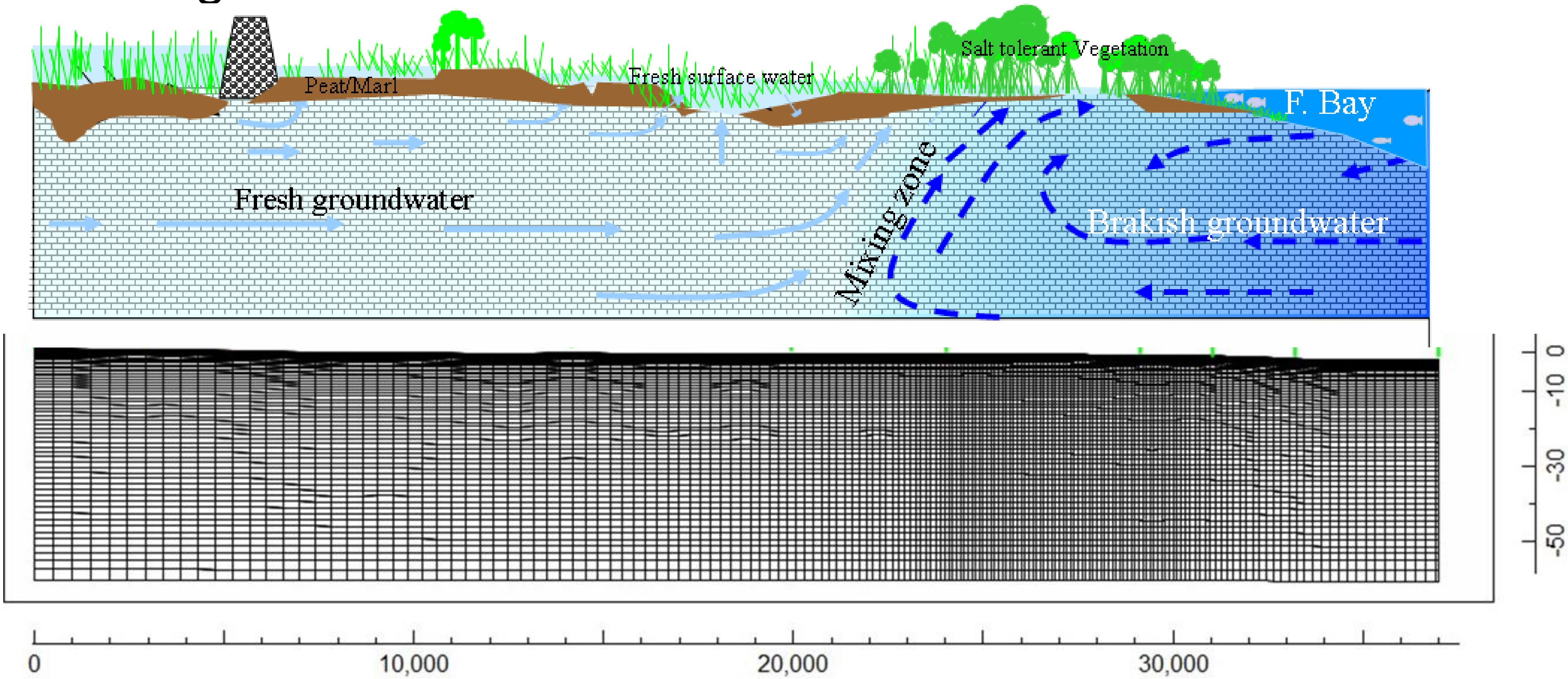
- Groundwater recharge and discharge areas
- Groundwater flow pattern





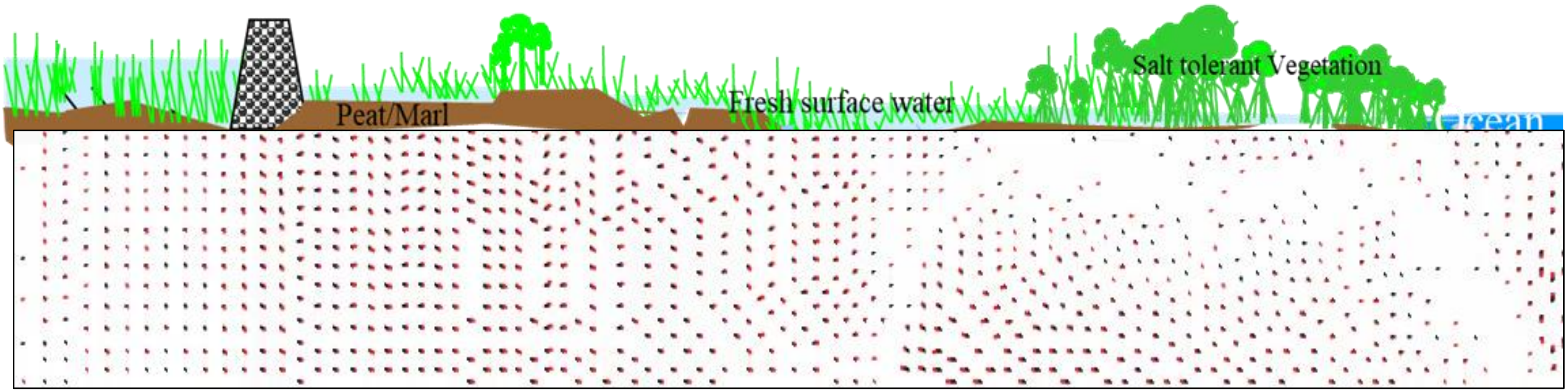
Ground- and Surface Water Interaction

- To simulate shallow groundwater flow pattern using SUTRA,
- To identify groundwater recharge/discharge areas, and
- To assess the dynamics of recent seawater intrusion in Taylor slough.



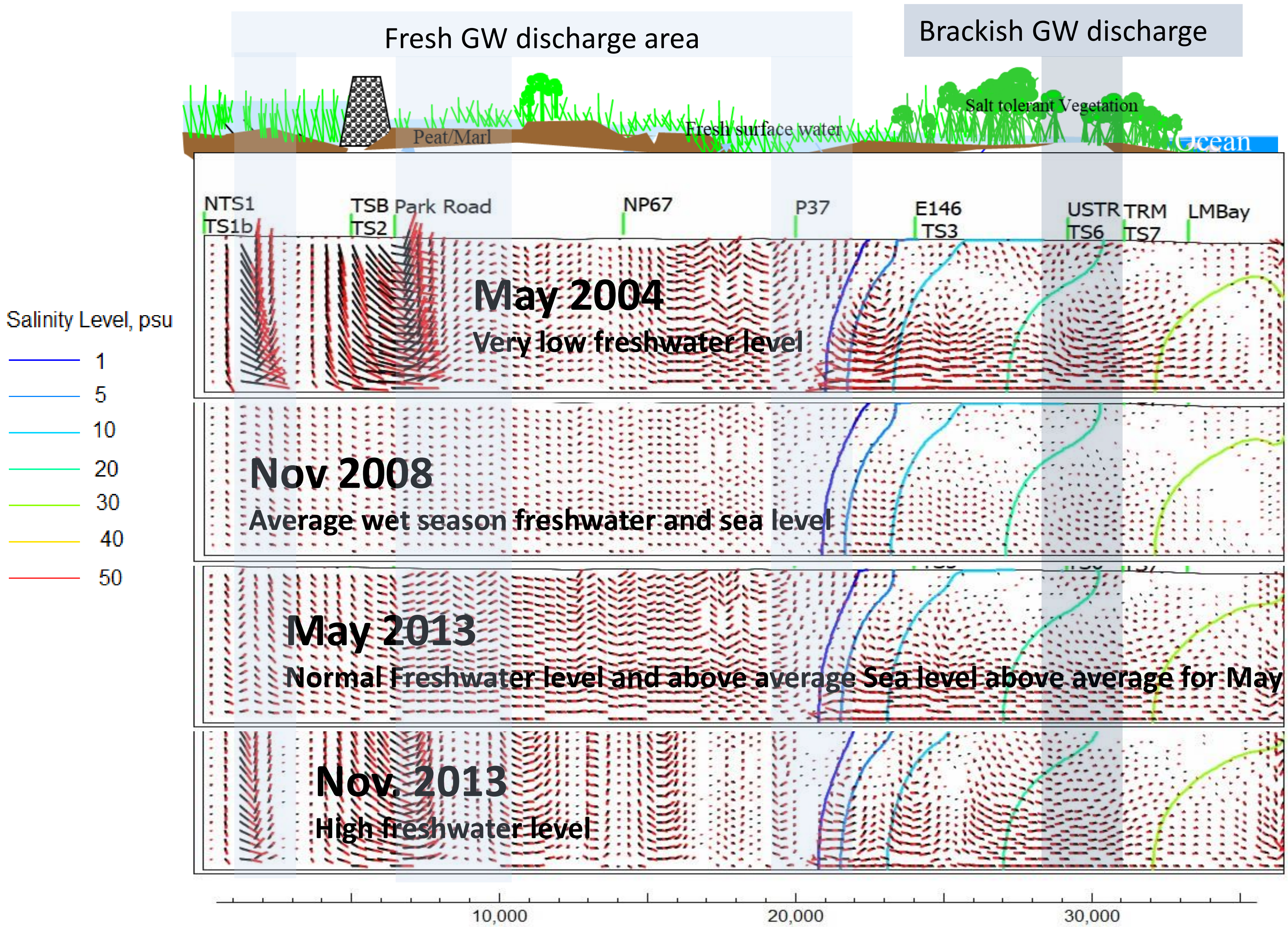
(Voss, 1999; Winston, 2009)

Result: Groundwater Flow Pattern (2000 to 2016)



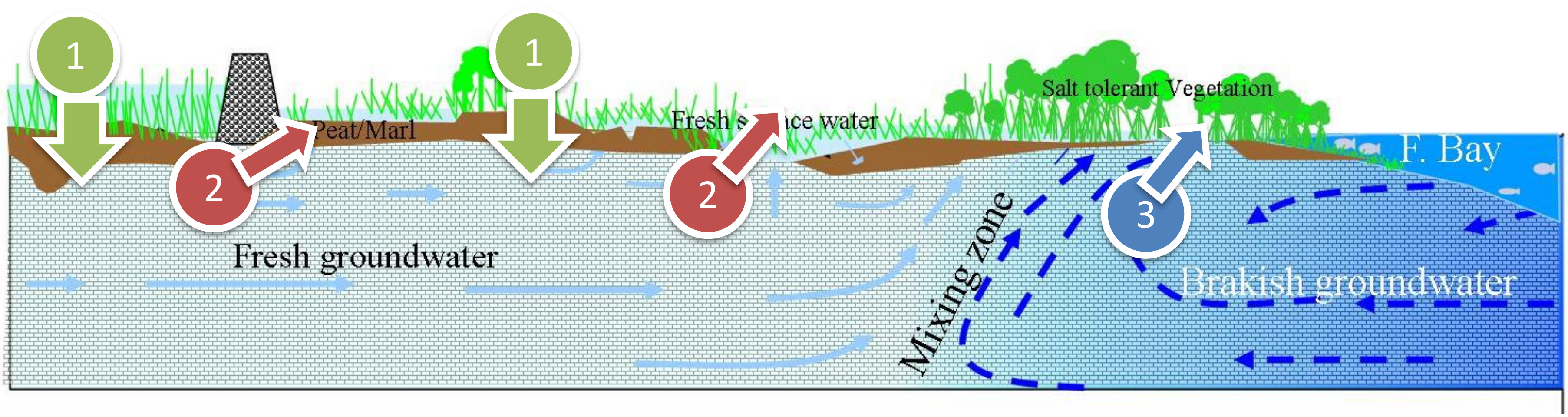
- Topographic features (slough, ridge, depression, roads) affect groundwater flow
- Groundwater recharge and discharge areas vary with surface water level, and thickness of Peat/marl layer

Result: Groundwater discharge areas



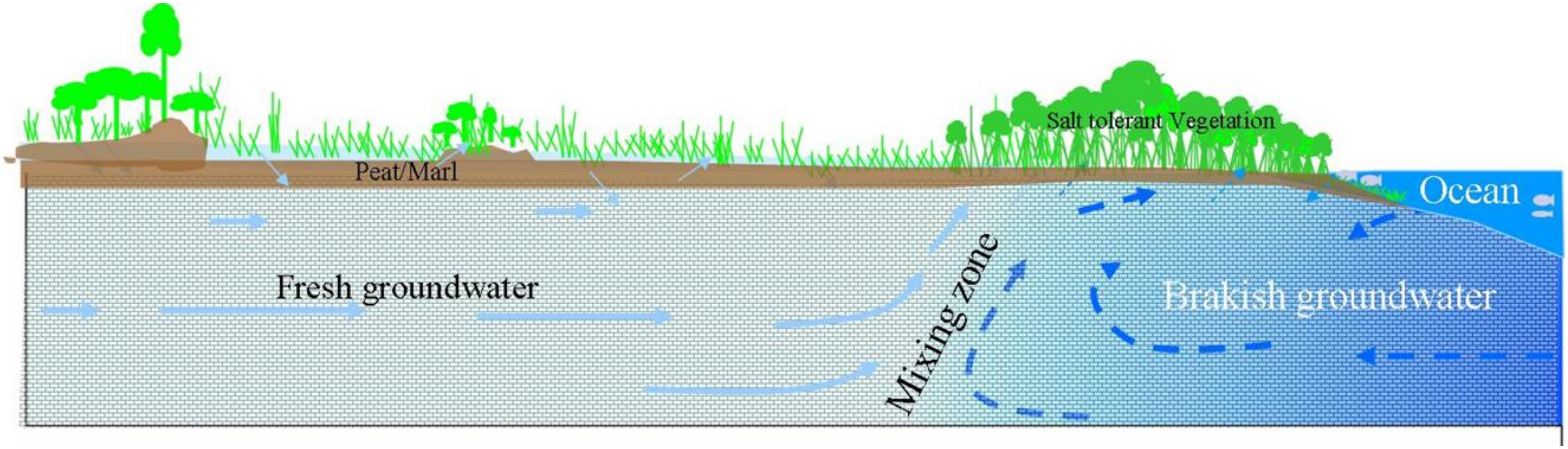
Summary

1. Freshwater recharge areas are upstream of park road and between TSB and P37.
2. Higher fresh groundwater discharge in relatively lower elevation areas of the slough and after Park road
3. Brackish groundwater discharge is in the white zone (between UTR/TsPh6 and shoreline).



Conclusions

- Coastal wetlands ecosystems are sensitive to saltwater intrusion and groundwater discharge.
- Wetland groundwater recharge and discharge areas depend on surface topography.
- Peat/marl layer may prevent saline groundwater discharge.
- Sea level rise may facilitate loss of peat/marl and push saline groundwater discharge further inland



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Thank YOU!

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